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REPORT NO. T 4/78

A COMPARISON OF FOUR INSTRUMENTS FOR MEASURING WBGT INDEX CORRELATIONS OF BOTSBALL WITH WBGT

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE
Natick, Massachusetts

8 SEPTEMBER 1978

UNITED STATES ARMY
MEDICAL RESEARCH & DEVELOPMENT COMMAND

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The ambient wet bulb globe temperature (WBGT) derived from three different WBGT kits, namely, (a) Weksler, (b) YSI, (c) Army and (d) the ambient wet globe temperature (WGT) measured by Botsball, were compared with the WBGT given by standard kit given in TB Med 175. At regular intervals (1) visual observations were made on the instruments and (2) an automated data collection system was used to record data from temperature sensors attached to the instruments. Significant differences in WBGT readings were found among the instruments, but the

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range for a given environment was usually less than 0.5°C. Readings taken by visual observations resulted in WBGT values which differed by less than 0.3°C from those calculated from the automated data collection system. By using an equation obtained for Botsball, it would be possible to modify the Botsball to read WBGY directly and to be a comparable instrument in determining environmental heat stress.

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TECHNICAL REPORT

No. T 4/78

A COMPARISON OF FOUR INSTRUMENTS FOR MEASURING WBGT INDEX; CORRELATION OF BOTSBALL WITH WBGT

by

B. ONKARAM, L.A. STROSCHEIN AND R.F. GOLDMAN

Project Reference 8 SEPTEMBER 1978 Series: ME-E3

US ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts 01760

ABSTRACT:

The ambient wet bulb globe temperature (WBGT) derived from three different WBGT kits, namely, a) Weksler, b) YSI, c) Army and d) the ambient wet globe temperature (WGT) measured by Botsball, were compared with the WBGT given by standard kit given in TB Med 175. At regular intervals 1) visual observations were made on the instruments and 2) an automated data collection system was used to record data from temperature sensors attached to the instruments. Significant differences in WBGT readings were found among the instruments, but the range for a given environment was usually less than 0.5°C. Readings taken by visual observations resulted in WBGT values which differed by less than 0.3°C from those calculated from the automated data collection system. By using an equation obtained for Botsball, it would be possible to modify the Botsball to read WBGT directly and to be a comparable instrument in determining environmental heat stress.

INTRODUCTION:

One of the indices used for expressing the severity of an environment in terms of the heat stress imposed on man, which has gained wide acceptance because of its apparent correlation with observed strain on the man, is the wet bulb globe temperature (WBGT) introduced by Yaglou and Minard (1957). Such an index has proved to be of value in eliminating adverse effects of heat at military training centers. It has also been shown that implementation of WBGT standards has reduced heat casualties in British troops (Peters, 1966). The National Institute of Occupational Safety and Health has also proposed the use of such an index as an indication of the degree of severity of health in heat stress environments (NIOSH, 1972).

The WBGT index combines the four basic factors that influence the degree of heat stress, namely, air temperature, vapor pressure, air movement and heat radiation. These factors are assessed by using a dry bulb, wet bulb and globe thermometer. The dry bulb thermometer is an ordinary mercury thermometer which measures air temperature. The wet bulb thermometer is also an ordinary mercury thermometer with a wick surrounding the bulb; it measures the effects of the evaporative cooling that occurs at the unsaturated vapor pressure conditions at a particular air temperature. The conventional dry and wet bulb thermometer readings are obtained with an air movement of at least 4.57 m/sec induced by a sling to rotate a pair of dry and wet bulb thermometers ("sling psychrometer") or by a motor driven fan, pulling air across the thermometer bulbs ("aspirating psychrometer"). A naturally convected wet bulb thermometer, however, has been adopted for human heat stress assessment; it is only affected by ambient air motion. The globe thermometer is a six inch, hollow copper sphere fitted with an ordinary thermometer; it senses the air temperature, air movement and heat radiation (Minard,1961). The WBGT index for outdoor use is computed by using the formula: 0.7 natural wet bulb temperature + 0.2 globe temperature + 0.1 dry bulb

temperature. The WBGT index for indoor use is computed by using the formula: 0.7 natural wet bulb temperature + 0.3 globe temperature.

Apart from WBGT index, various indices like effective temperature (ET), corrective effective temperature (CET) and heat stress index (HSI) have been used (Witherspoon and Goldman, 1973). Botsford (1971) developed a wet globe thermometer which consists of a dial thermometer with the heat sensor enclosed by a 2 3/8" black copper sphere completely covered with a black cloth; this instrument, now known as the "Botsball", measures wet globe temperature (WGT) (Fig. 1c).

The TB Med 175 (1969) prescribes the use of the wet bulb globe temperature index to characterize the environment, and the appropriate action to take at different values to reduce heat illness. It also describes in detail, the various components needed and the procedures to be followed in setting up the WBGT kit (Fig. 1A). In the following description the kit described in the above bulletin is referred to as the standard WBGT kit or the standard kit for the sole purpose of convenience.

Today other instruments are available which measure WBGT index directly and which measure the three different temperatures from which the WBGT index can be computed. Taylor et al. (1969) developed a fluid analogue computer based on the mercury-in-glass thermometer to measure WBGT index directly. Luper (1965) described a silicone diode circuit for direct measurement of WBGT index. The Weksler Instruments Corporation, under US Army contract, developed a wet bulb globe temperature kit which measures the dry, wet bulb and globe temperatures from which WBGT can be calculated by using a slide rule provided in the kit (Fig. 1B). For the black globe thermometer, this kit makes use of a hollow copper cylinder painted black and enclosed in a transparent, perforated plastic shield. The current version of the kit is known as wet bulb/globe temperature kit,

NSN 6665-00-159-2218 and is available from USAMBRDL, Fort Detrick, Frederick, MD 21701. The Yellow Springs Instruments Co., Inc. also supplies a kit that can be used to measure the WBGT index both indoors and outdoors; the WBGT index as well as the individual temperatures can be directly read on the meter provided. This kit makes use of a six inch hollow globe, as does the standard kit, and is referred to as the YSI heat stress instrument, or YSI, in the following description (Fig. 1D). An earlier prototype equipment which directly gives WBGT index, was fabricated by US Army Medical Equipment and Development Laboratory, when it was located at Fort Totten, NY; this is referred to as the Army kit. Only three kits were made and they are not available commercially.

Brief and Confer (1971) compared wet globe temperature (WGT), effective temperature (ET), corrected effective temperature (CET) and heat stress index (HSI) with WBGT. They showed a good relation between WGT and WBGT and came up with the following equation: WGT = 0.958 WBGT − 3.2 in $^{\circ}$F, or WBGT = 1.044 WGT − 2.64 in $^{\circ}$C. They derived the correlation from 34 sets of data collected in a test chamber.

Mutchler and Vecchio (1977) developed empirical relationships among heat stress indices derived from a series of studies from 14 hot industries. They developed equations for the various indices with WBGT at various wind velocities; in the overall range they showed a good relation between WGT and WBGT, and suggested the relationship WBGT = 1.05 WGT + 1.14 in $^{\circ}$C.

Ciriello and Snook (1977) studied the relationship between WGT and WBGT under varied radiant, humidity, windspeed and dry bulb temperature conditions. They concluded if radiation, humidity and air movement are available, WGT can precisely predict the WBGT within acceptable limits. The equation WBGT = 1.07 WGT + 0.80 in $^{\circ}$C was given for all environments.

All the above studies indicate a relationship of WGT with WBGT in indoor

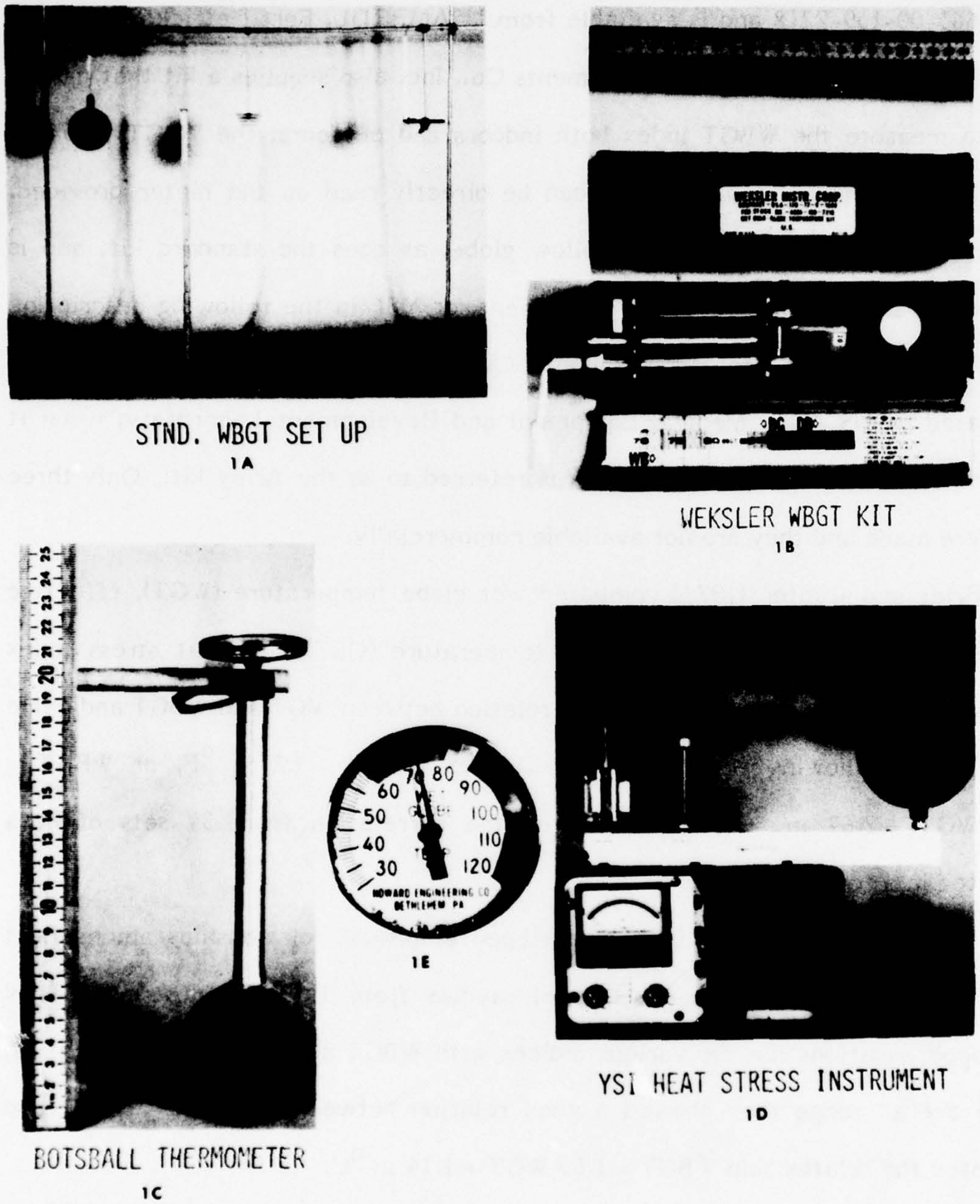

Fig. 1. Instruments used in the study.

environments, and for computing WBGT, the relation WBGT = 0.7 natural wet bulb + 0.3 globe is used.

The purpose of this present investigation is to compare 1) an early Army kit, 2) the adopted US Army Weksler kit and 3) the YSI kit with the standard kit, and at the same time, to compare the ambient WGT described by Botsball with the WBGT obtained by using the standard kit. The WBGT indices given by these kits, as well as their individual component readings, namely, the dry bulb, the wet bulb and the globe temperatures are to be compared with the respective temperatures from the standard kit. It is an attempt to see whether these kits really conform to the standard kit as they have been built to simulate the standard kit, but differ from the standard, in that the dry bulbs are shaded differently and placed differently in each kit and a black globe analog is used in the case of Weksler for the six inch globe.

METHODS:

It was decided to carry out the experimentation on the roof top of the United States Army Research Institute of Environmental Medicine (USARIEM) building where facilities are available to station the recording instruments used in the study. After a careful consideration of the various structures present on the roof of the building, a location was chosen where the instruments did not receive radiation from other structures, did not get shaded and did not get cut off from the wind.

To measure the temperatures from the instruments copper-constantan thermocouples were used. As it was necessary to measure the globe, the wet bulb and the dry bulb temperatures from each WBGT kit, a three point, copper-constantan, Type I, thermocouple harness was used. Thermocouples were tied to the bulb of the thermometers in the case of standard and Weksler kits. The thermocouples were attached to the sensors on the Army and YSI kits by using a

thin, two-sided, tape adhesive. In the case of Botsball, the dial portion of the instrument was cut and the thermocouple introduced into the stem. The harnesses were connected to low thermal decade switches (decades) in an HP scanner.

A Cambridge systems instrument, 110 automatic meteorological and dew point measuring system which measures ambient temperature and dew point was connected to the decades in the scanner. An Eppley pyranometer which measures radiation was connected to the decades in the scanner. A three-cup anemometer which measures wind speed, was connected to an HP universal counter. A HP digital voltmeter was used to read the thermocouples in conjunction with a HP timing generator and a HP-IB digital clock. The HP scanner, HP universal counter, HP digital voltmeter, HP timing generator and HP-IB digital clock were connected to an IEEE standard digital interface with an HP 9825A calculator. The layout of the various instruments is given in Fig. 2.

The standard kit was set up as described in the TB Med 175. Retort stands with six-foot long rods were used as supports to hold a horizontal rod four feet above the ground. The globe thermometer was constructed from a 6" globe and an ordinary mercury thermometer. The wet bulb thermometer was constructed from an ordinary thermometer with a wick tied to the bulb and dipped in distilled water filled up to the neck in a 50 ml conical flask. The dry bulb thermometer was an ordinary thermometer that was shielded from the sun by aluminum plates. The globe thermometer, the dry bulb thermometer and the wet bulb thermometer were hung separated by a distance of two feet from each other on the horizontal rod.

The Army kit was set up on its own tripod to the left of the standard kit at the same height. As the legs of the tripod are not strong enough to prevent the instrument from tipping over due to wind, lead weights were attached to them. The wet bulb reservoir of the Army kit was filled with distilled water. The Army kit was positioned so that the dry bulb sensor was shaded from the sun.

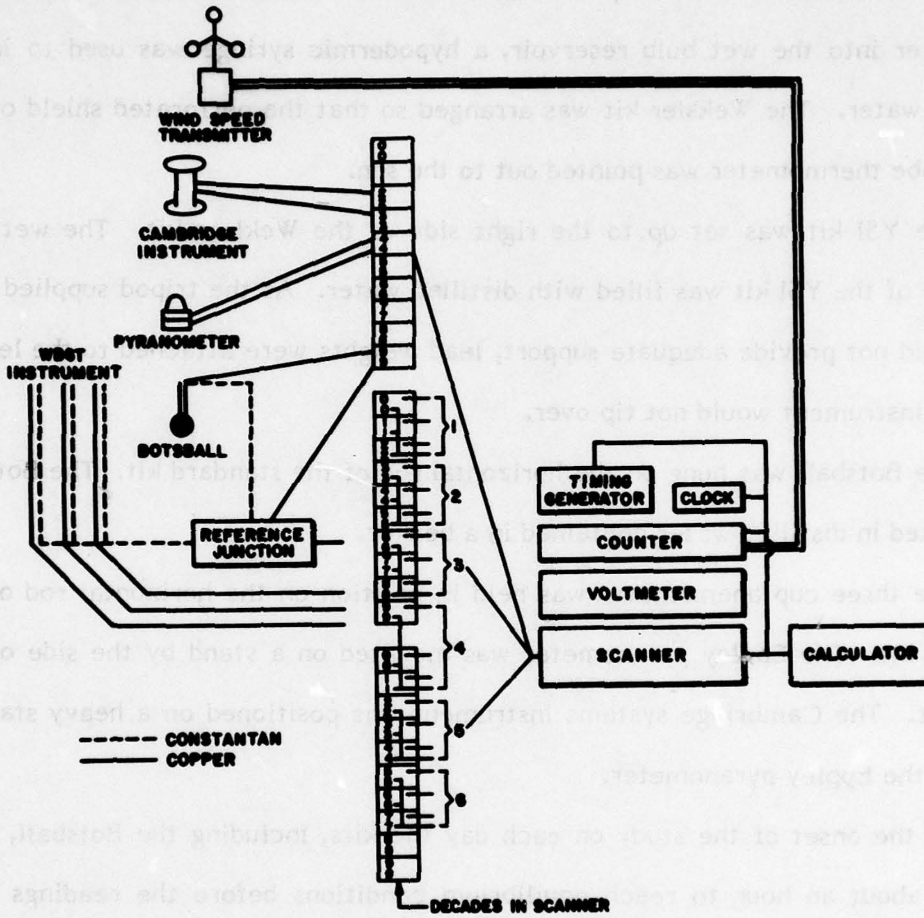

FIG. 2 TYPICAL LAYOUT OF THE AUTOMATED DATA ACQUISITION SYSTEM. SIX INSTRUMENTS CAN BE CONNECTED AS SHOWN.

The Weksler kit was set up to the right side of the standard kit. The kit was held in position on a screw attached to the clamp of a retort stand. The wet bulb reservoir of the kit was filled up with distilled water. As it was a little difficult to pour water into the wet bulb reservoir, a hypodermic syringe was used to inject distilled water. The Weksler kit was arranged so that the perforated shield of the black globe thermometer was pointed out to the sun.

The YSI kit was set up to the right side of the Weklser kit. The wet bulb reservoir of the YSI kit was filled with distilled water. As the tripod supplied with the kit did not provide adequate support, lead weights were attached to the legs so that the instrument would not tip over.

The Botsball was hung on the horizontal rod of the standard kit. The Botsball was dunked in distilled water contained in a beaker.

The three cup anemometer was held in position on the horizontal rod of the standard kit. The Eppley pyranometer was mounted on a stand by the side of the Army kit. The Cambridge systems instrument was positioned on a heavy stand in front of the Eppley pyranometer.

At the onset of the study on each day the kits, including the Botsball, were left for about an hour to reach equilibrium conditions before the readings were made. The wet bulb reservoirs of all the kits were checked from time to time for distilled water. The wicks of the wet bulbs were checked for cleanliness. The Botsball was dunked from time to time to keep it adequately wet. The position of the Army kit was changed from time to time to see that the dry bulb was shaded from the sun. Once a week the condition of the batteries in the Army kit were checked and replaced as necessary. As the YSI kit needs charging after about 30 hours of continuous use, it was recharged. The instruments were left indoors at the end of each run. The YSI kit was observed to give erratic readings after it was wetted by rain.

The HP9825A calculator was programmed to read the thermocouples at intervals of 30 seconds and a five minute average was computed and recorded on a HP 9162-0061 data cartridge. Visual observations were made on the WBGT measuring kits every 20 minutes to see that the readings from the automated data collection system agreed with the visual readings. The calculator was programmed to "beep" at intervals of 20 minutes to remind the observer to take the visual readings. By using the special function keys on the calculator, the individual readings of the three sensors in each WBGT measuring kit, as well as the Botsball, were displayed whenever they were needed. The wind speed, the dew point and radiation were also displayed when needed by using the special function keys.

RESULTS AND DISCUSSION:

The ranges of environmental conditions that prevailed during the study were as follows: ambient air temperature 18.7°C to 34.6°C, dew point 7°C to 24.9°C, radiation 0 to 1500 W/sq.m and windspeed 0 to 7 m/s.

A paired t-test was done between the WBGT calculated from visual observations and the WBGT obtained from the automated data collection system. When a hypothetical difference of zero was assumed between the two sets of data, significant differences were found in 16 out of 36 sets; however, the mean differences were within 0.3°C, except for four, which were accounted for by problems in the instrumentation on those particular days. This shows that data collected by the automated data acquisition system are in good agreement with the visual measurements, which are normally taken in practice.

For the purpose of analyzing and correlating the extensive meteorological data collected by the automated data acquisition system, the days on which the experiment was carried out have been divided into the following four groups: 1) clear sky and sunny, 2) clear sky, sunny and hazy, 3) partly cloudy and 4) overcast weather.

By using the formula WBGT = 0.7 natural wet bulb + 0.2 globe + 0.1 dry bulb, WBGT was calculated for each kit from the globe, dry bulb and wet bulb readings.

A two way analysis of variance was carried out on the WBGT data for each day in the individual groups. Significant differences were found among the instruments. The differences are variable and it is difficult to make generalized conclusions; namely, which kit reads high or low compared to the standard kit. Although significant differences were observed, most of the differences were less than 0.5^{o}C, a relatively minor difference with respect to appreciation of such indices.

It was decided to evaluate the effect of radiation on the WBGT reading and the individual component, namely, globe, dry bulb and wet bulb temperatures when compared to the standard kit. The plots are presented in Figures 3 to 6. Each dot in the plot represents a data point. Figure 3 represents the difference between the instrument WBGT and the standard WBGT as a function of radiation. As can be seen from the figure, the Army and the Weksler kits give higher WBGT readings than the standard kit at radiation ranging from 400 to 1050 W/sq.m, compared to YSI. Figure 4 represents the difference in globes as a function of radiation. The Army kit globe reads low with increasing radiation. It may be because the globe is positioned close to the control box. The Weksler black globe analog seems to agree with the standard globe at low radiation ranging from 0 to 250 W/sq.m, but deviates a lot at higher radiation values. The YSI globe seems to agree well with the standard globe. Figure 5 represents the difference between dry bulbs as a function of radiation. The dry bulbs of the three kits read higher than the standard dry bulb. This is because of the inadequate shading of dry bulbs in these kits. Compared to the other two kits, the YSI dry bulb seems to read closer to the standard dry bulb. Figure 6 represents the difference between wet bulbs as a function of radiation. The Army kit wet bulb and the Weksler wet bulb read high

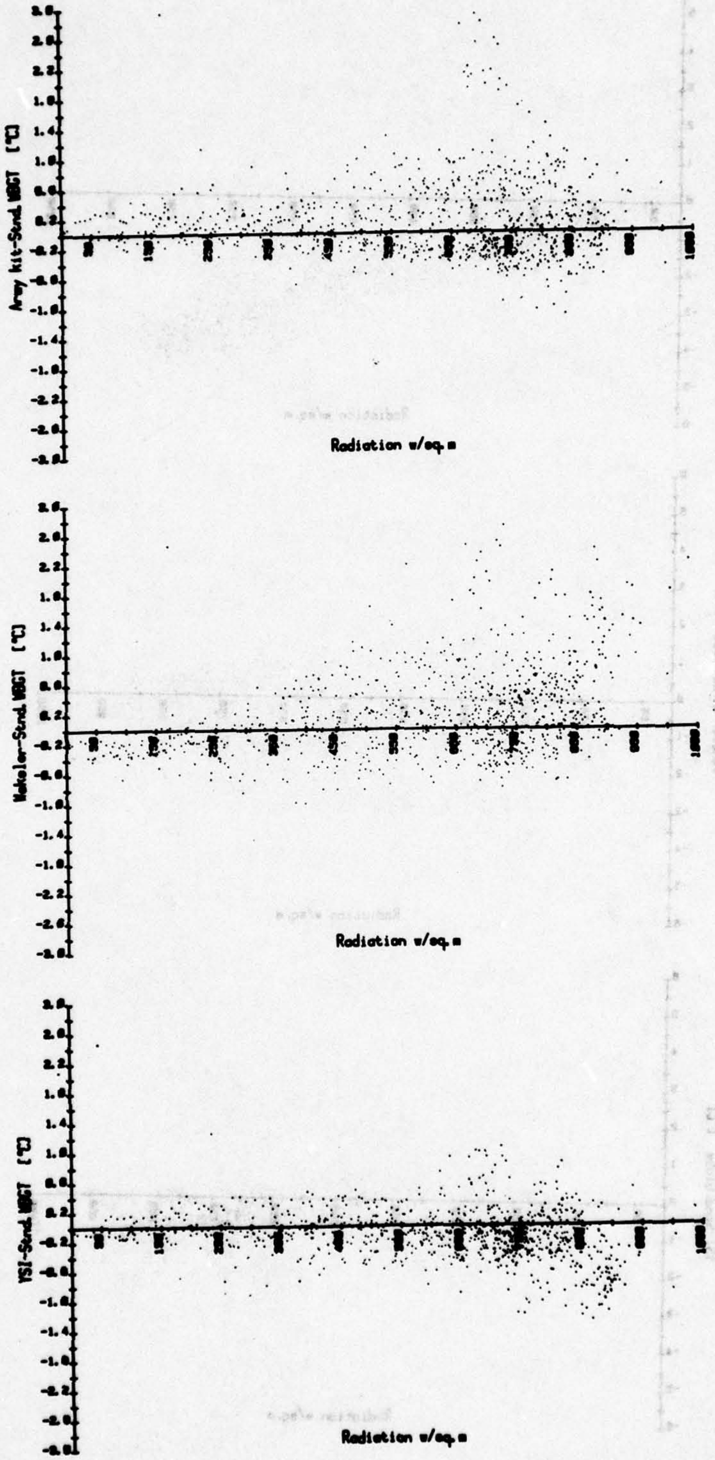

Fig. 3. Difference between Instrument WBGT and Standard WBGT as a function of radiation.

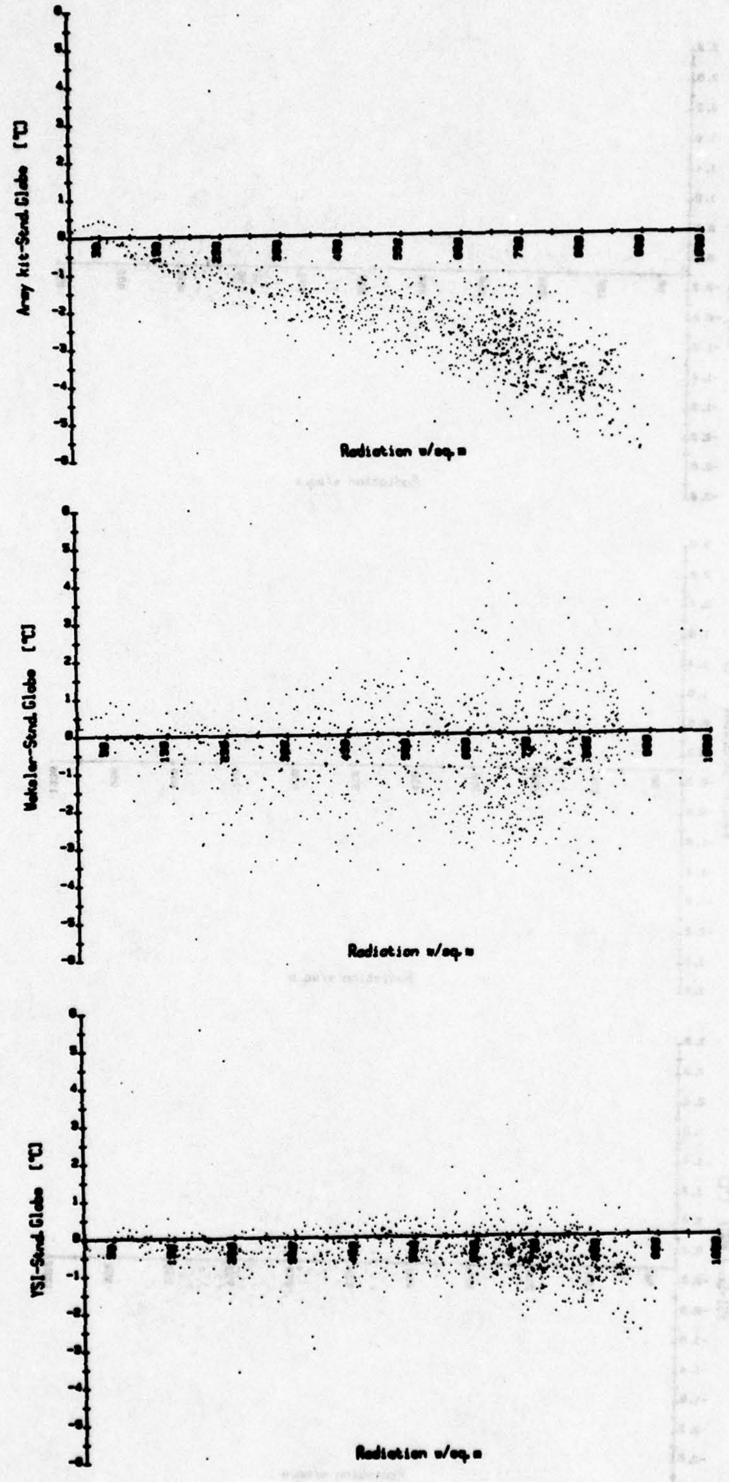

Fig. 4. Difference between Instrument Globe and Standard Globe as a function of radiation.

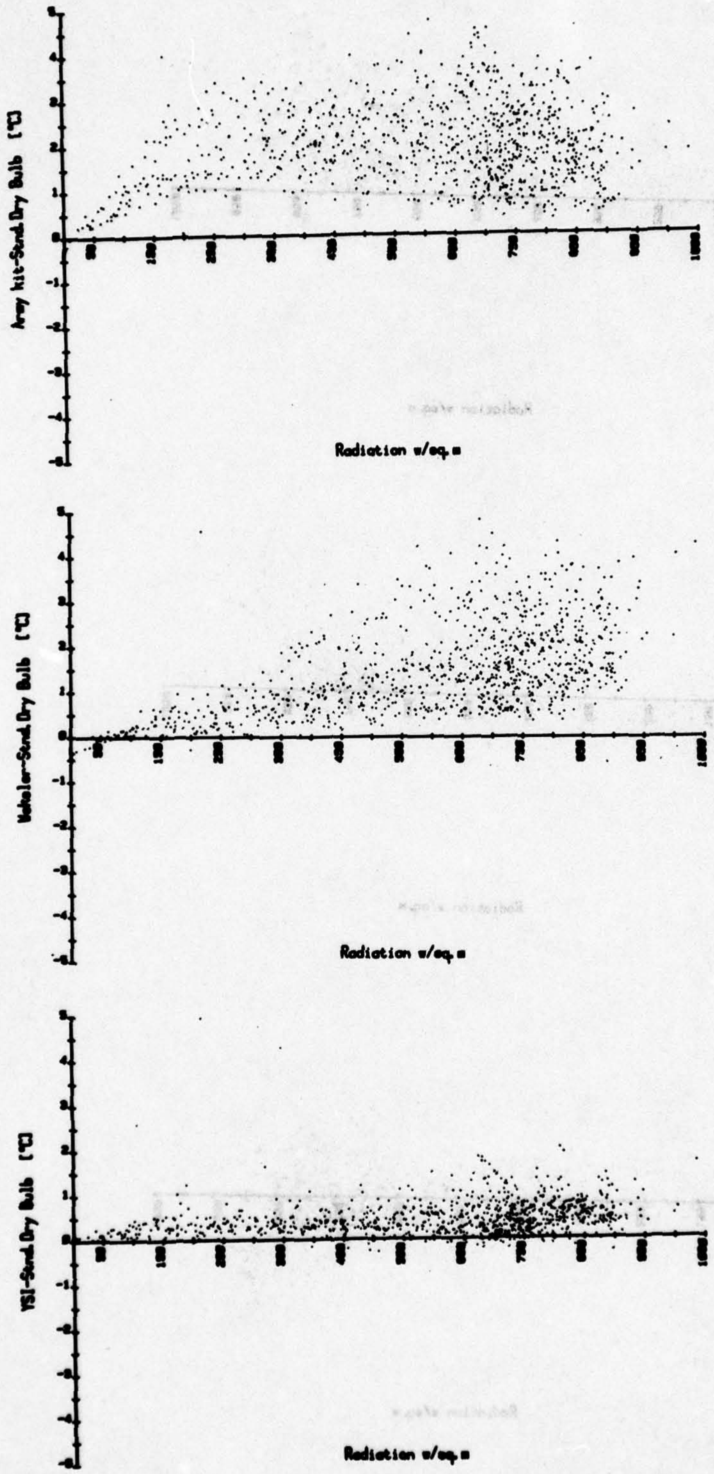

Fig. 5. Difference between Instrument Dry Bulb and Standard Dry Bulb as a function of radiation.

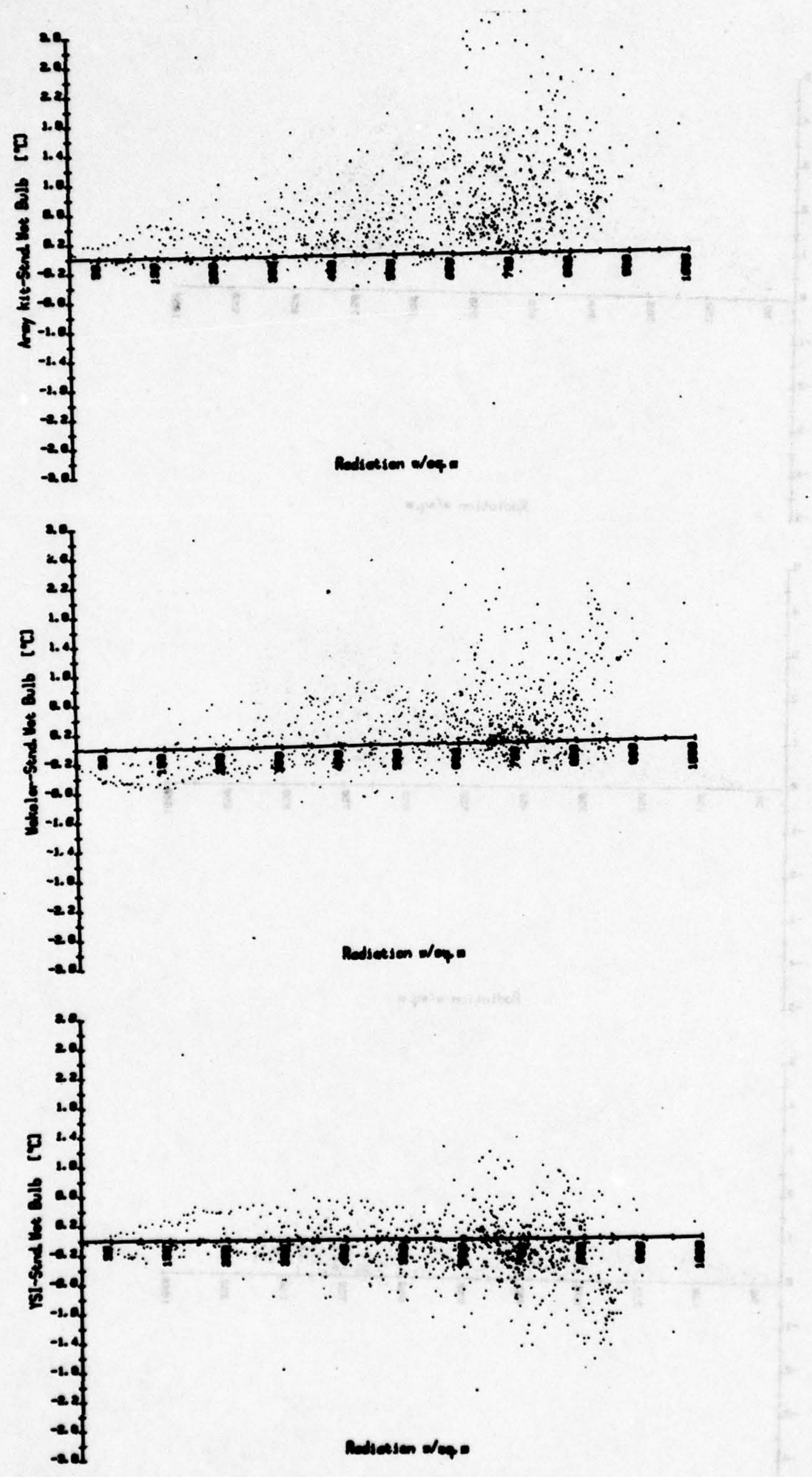

Fig. 6. Difference between Instrument Wet Bulb and Standard Wet Bulb as a function of radiation.

with radiation increasing from 350 to 950 W/sq.m. It may be because of their configuration. The YSI wet bulb seems to agree well with the standard wet bulb.

The effect of windspeed was evaluated on the kits and the plots shown in Figures 7 to 10. Figure 7 represents the difference between instrument WBGT and the standard WBGT as a function of windspeed. The Army kit and the Weksler kit register high WBGT values at windspeeds ranging from 1 to 3 m/s. Above 3 m/s they seem to agree well with the standard kit. The YSI WBGT deviates less from the standard WBGT. Figure 8 represents the difference between globes as a function of windspeed. The Army kit globe and the Weksler black globe analog read lower than the standard globe. The YSI globe agrees well with the standard globe. Figure 9 represents the difference in dry bulbs as a function of windspeed. The dry bulbs of the three kits register higher values than the standard dry bulb at low windspeeds and tend to agree at high windspeeds. Figure 10 represents the difference in wet bulbs as a function of windspeed. The Army kit wet bulb reads high at low windspeeds and it tends to agree at higher windspeeds. This may be due to inadequate cooling at low windspeeds and also the position of the wet bulb in the Army kit, which does not permit it to be exposed to the wind from all directions. The Weksler wet bulb also reads high at low windspeeds but not as pronounced at that of the Army kit wet bulb. This phenomenon may be due to the insufficient evaporative cooling that occurs at the wet bulb and also the way the wick hangs from the bulb of the thermometer. The YSI wet bulb seems to diverge little from the standard wet bulb compared to the other two kits.

Overall comparisons were made between the globe, dry bulb and wet bulb thermometer reading of each instrument with the same component in the standard kit. The plots are presented in Figures 11 to 13. Figure 11 represents the plots between globe of each instrument with the standard globe. The Army kit globe and the Weksler kit black globe analog read lower than the standard kit. The YSI globe

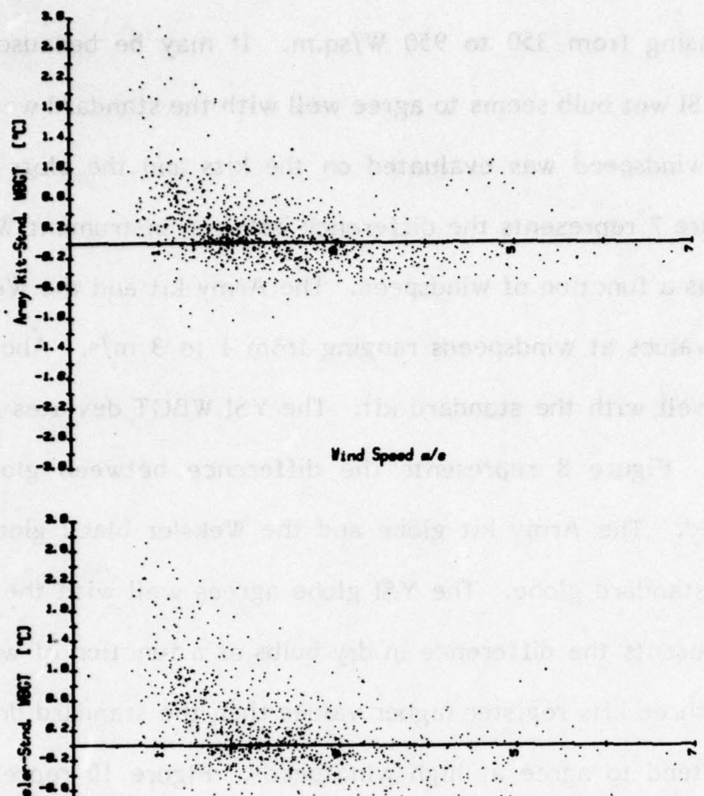

Fig. 7. Difference between Instrument WBGT and Standard WBGT as a function of wind speed.

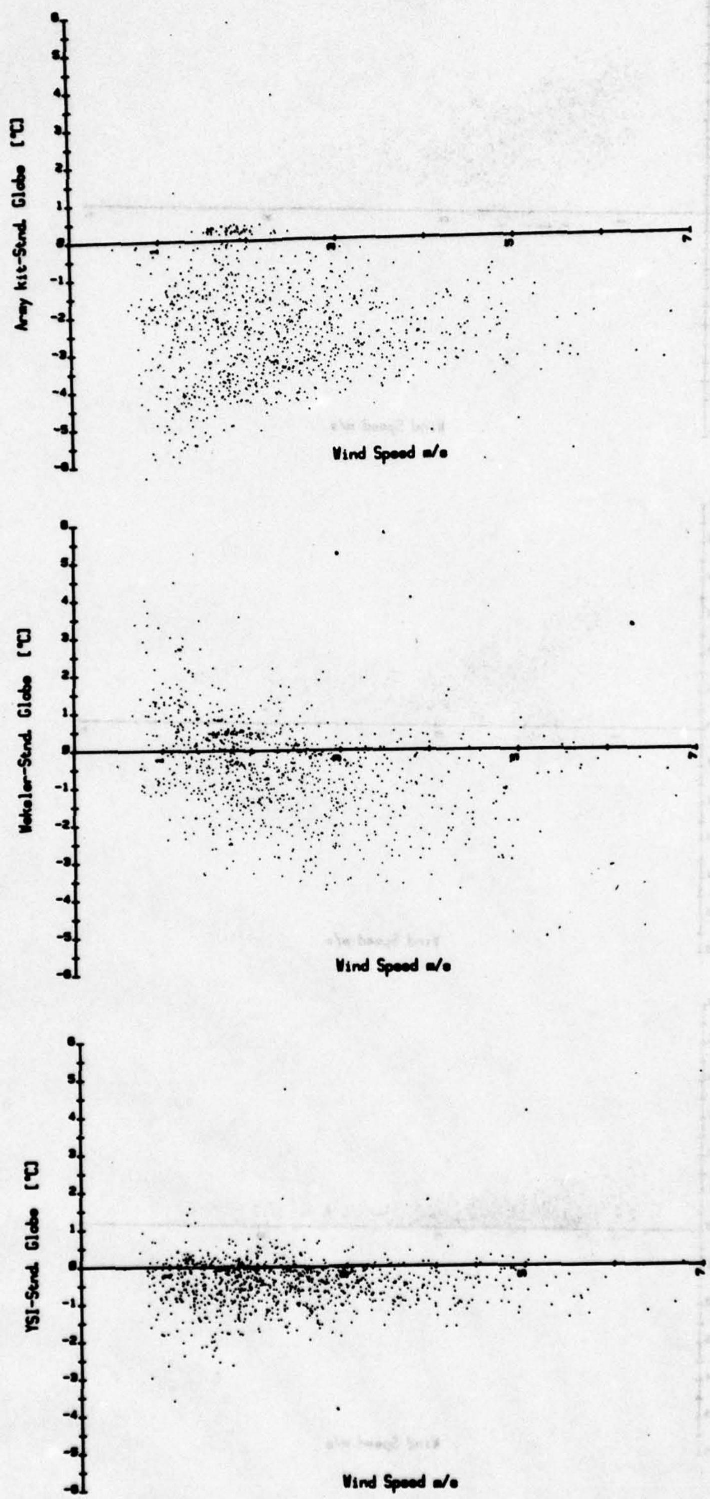

Fig. 8. Difference between Instrument Globe and Standard Globe as a function of wind speed.

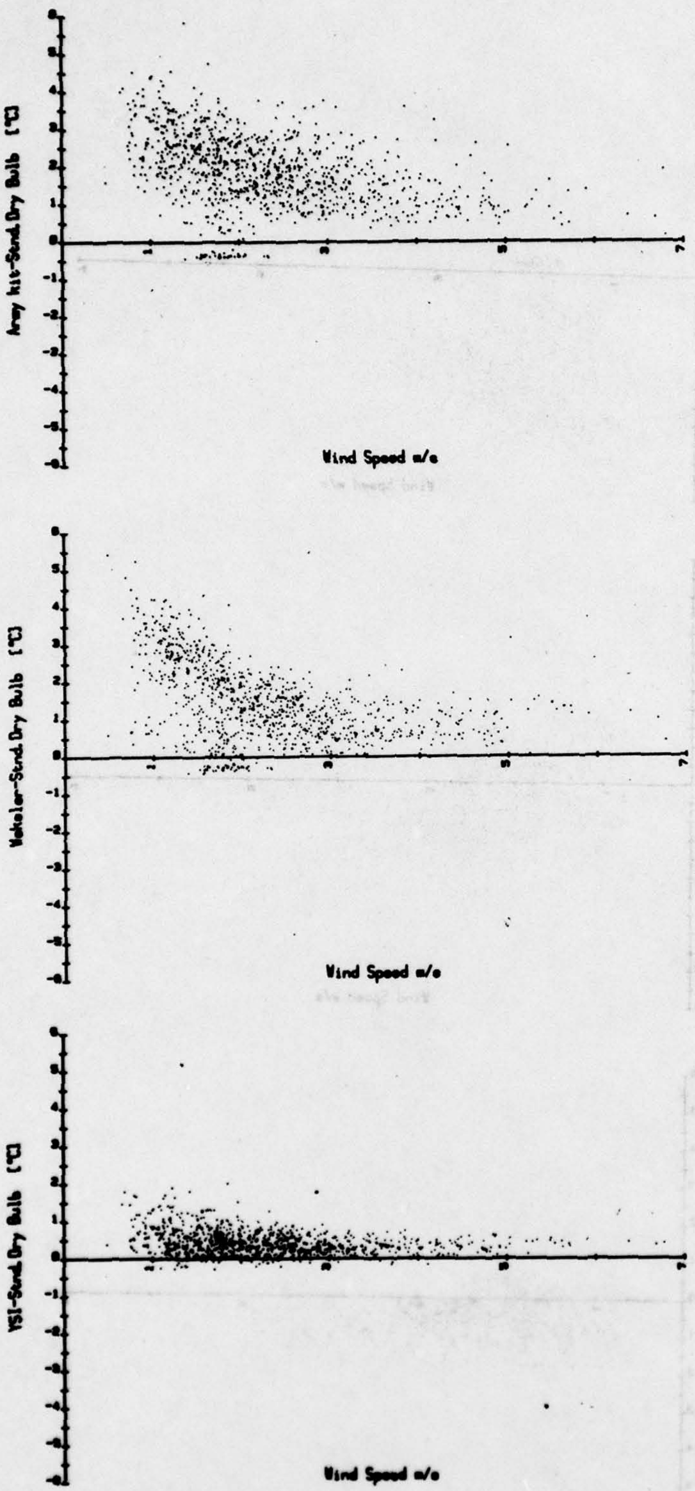

Fig. 9. Difference between Instrument Dry Bulb and Standard Dry Bulb as a function of wind speed.

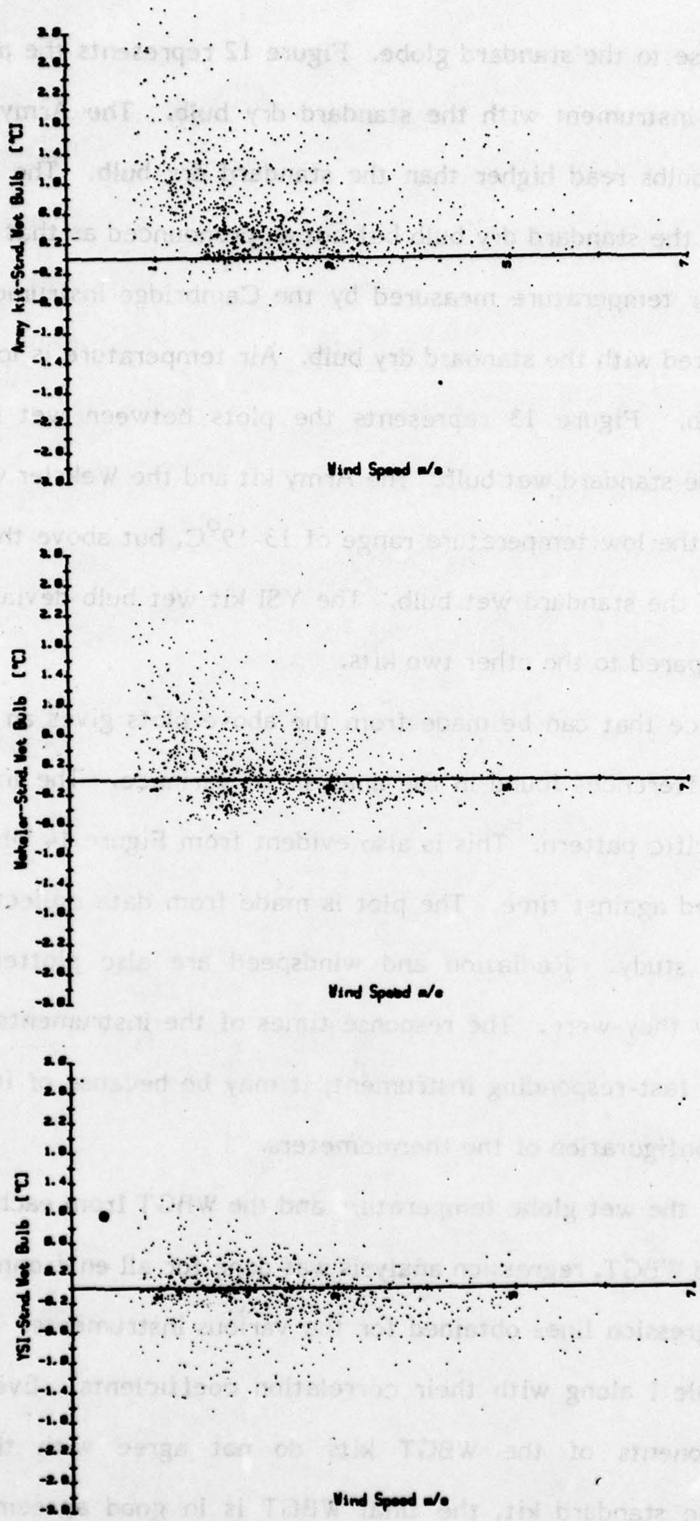

Fig. 10. Difference between Instrument Wet Bulb and Standard Wet Bulb as a function of windspeed.

seems to read close to the standard globe. Figure 12 represents the plots between dry bulb of each instrument with the standard dry bulb. The Army kit and the Weksler kit dry bulbs read higher than the standard dry bulb. The YSI dry bulb reads higher than the standard dry bulb but not as pronounced as that of the other two kits. The air temperature measured by the Cambridge instrument described above was compared with the standard dry bulb. Air temperature is lower than the standard dry bulb. Figure 13 represents the plots between wet bulb of each instrument and the standard wet bulb. The Army kit and the Weksler wet-bulbs are always higher in the low temperature range of 13-19°C, but above this range they diverge less from the standard wet bulb. The YSI kit wet bulb deviates less from the standard compared to the other two kits.

The inference that can be made from the above plots gives an indication of the significant differences found in the analysis of variance. The instruments do not follow a specific pattern. This is also evident from Figure 14 where WBGT of each kit is plotted against time. The plot is made from data collected on one of the days in the study. Radiation and windspeed are also plotted to give an indication of how they were. The response times of the instruments are varying. The Weksler is a fast-responding instrument; it may be because of its black globe analog and the configuration of the thermometers.

To see how the wet globe temperature and the WBGT from each kit correlate with the standard WBGT, regression analysis was done for all environments. Figure 15 shows the regression lines obtained for the various instruments. The equations are given in Table I along with their correlation coefficients. Even though the individual components of the WBGT kits do not agree with the respective component in the standard kit, the final WBGT is in good agreement with the standard WBGT. This is evident from Table I. The slope of the regression line obtained for Botsball obtained in this study is identical to the slope of the

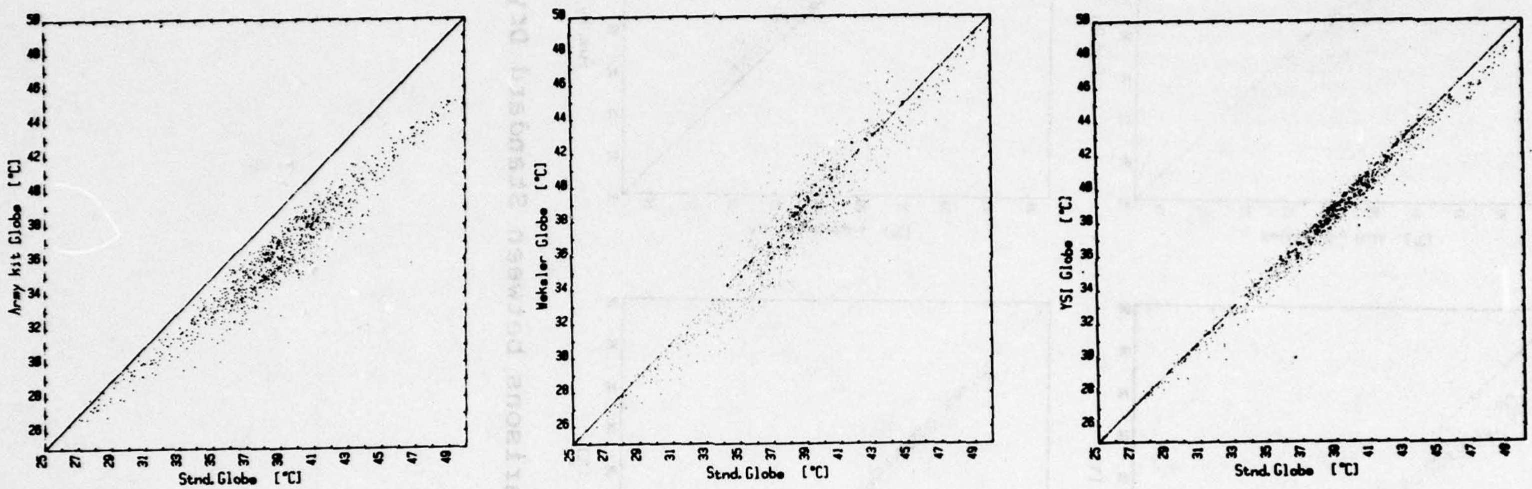

Fig. 11. Overall comparisons between Standard Globe and Instrument Globe.

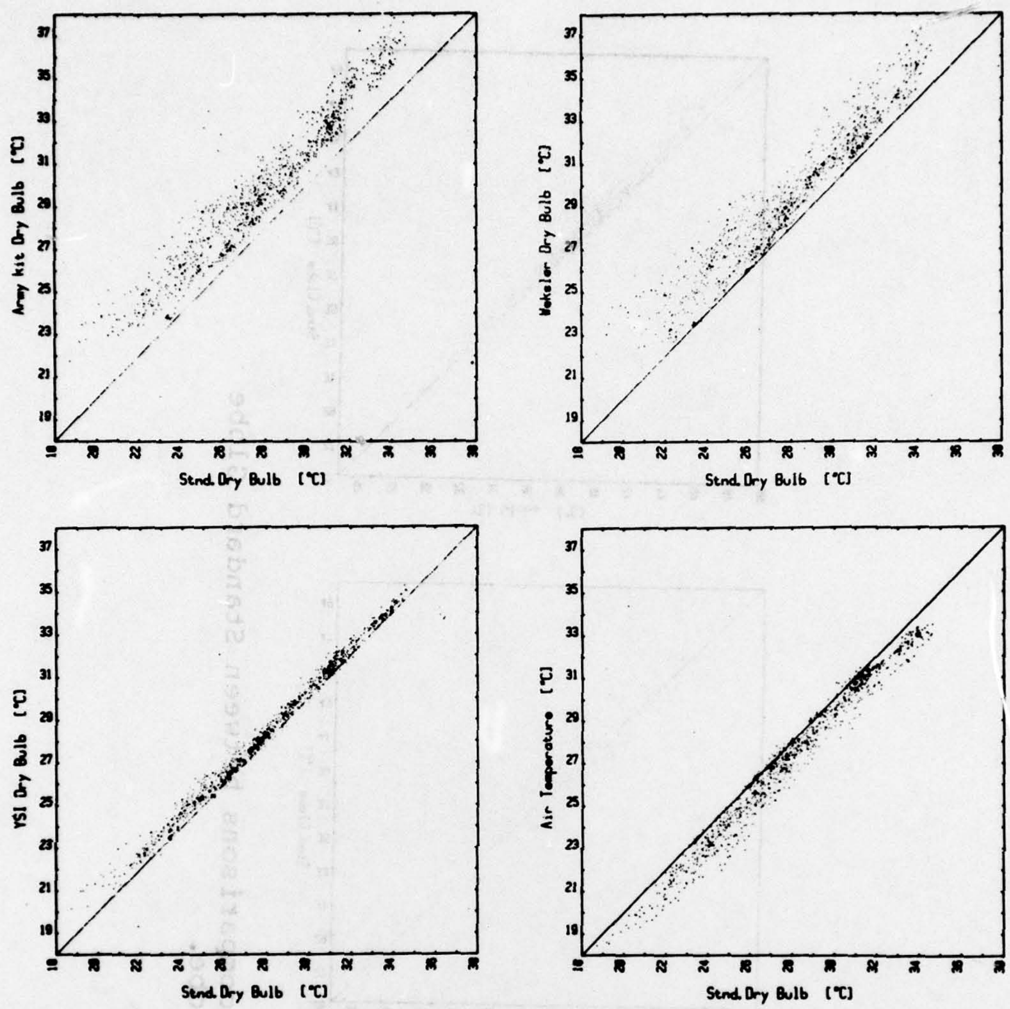

Fig. 12. Overall comparisons between Standard Dry Bulb and Instrument Dry Bulb.

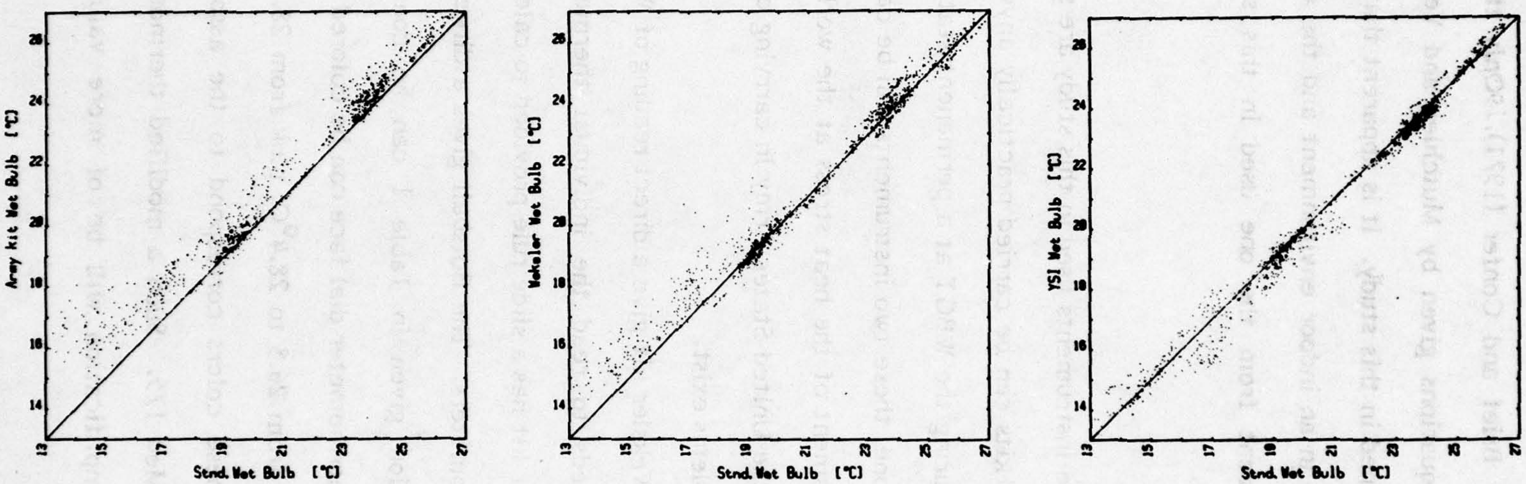

Fig. 13. Overall comparisons between Standard Wet Bulb and Instrument Wet bulb.

regression equation given by Brief and Confer (1971). Only the intercepts are different. The regression equations given by Mutchler and Vecchio (1977) are different from the ones obtained in this study. It is apparent that studies by these investigators were conducted in an indoor environment and the equation used for computing WBGT was different from the one used in this study, which was conducted outdoors.

CONCLUSIONS:

The relative sizes of the instruments used in this study are shown in Figure 1. The Botsball and the Weksler kits can be carried practically anywhere to measure heat stress. Instead of measuring the WBGT at a permanent station and conveying it to a place where work is done, these two instruments can be carried right to the site of work to get an assessment of the heat stress at the work site. This is an important consideration for the United States Army in carrying out its missions at places where heat stress problems exist.

The Army kit and the Weksler kit give a direct reading of WBGT. In the case of the standard kit one needs to read the individual thermometers and then compute WBGT. The Weksler kit has a slide rule provided to calculate WBGT after reading the individual thermometers. The Botsball gives a direct reading of WGT which, by using the equation given in Table 1 can be converted to WBGT. Alternatively, the Botsball thermometer dial face can be colored as follows: green for less than 26.8°C, yellow from 26.8 to 28.4°C, pink from 28.4 to 30°C and red for greater than 30°C. These colors correspond to the associated risk zones indicated by WBGT in TB Med 175. Such a modified thermometer is shown in Fig. 1E. This modified simplification will be of more value in use of this instrument.

The Botsball, the Weksler kit and the YSI kit are commerically available. The Army kit is a prototype instrument. The six inch globe needed to construct a

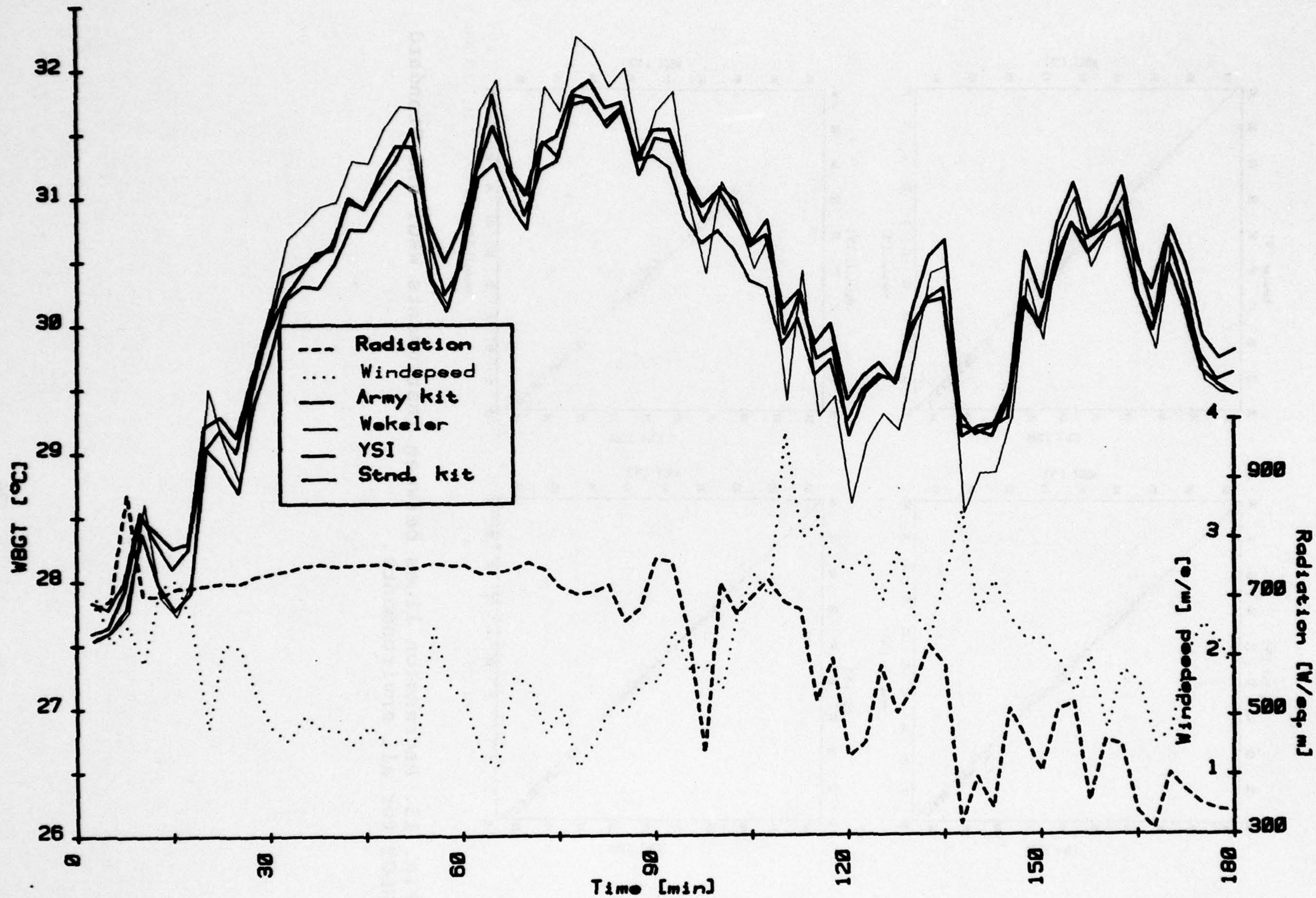

Fig. 14 Time course of WBGT from the four instruments.

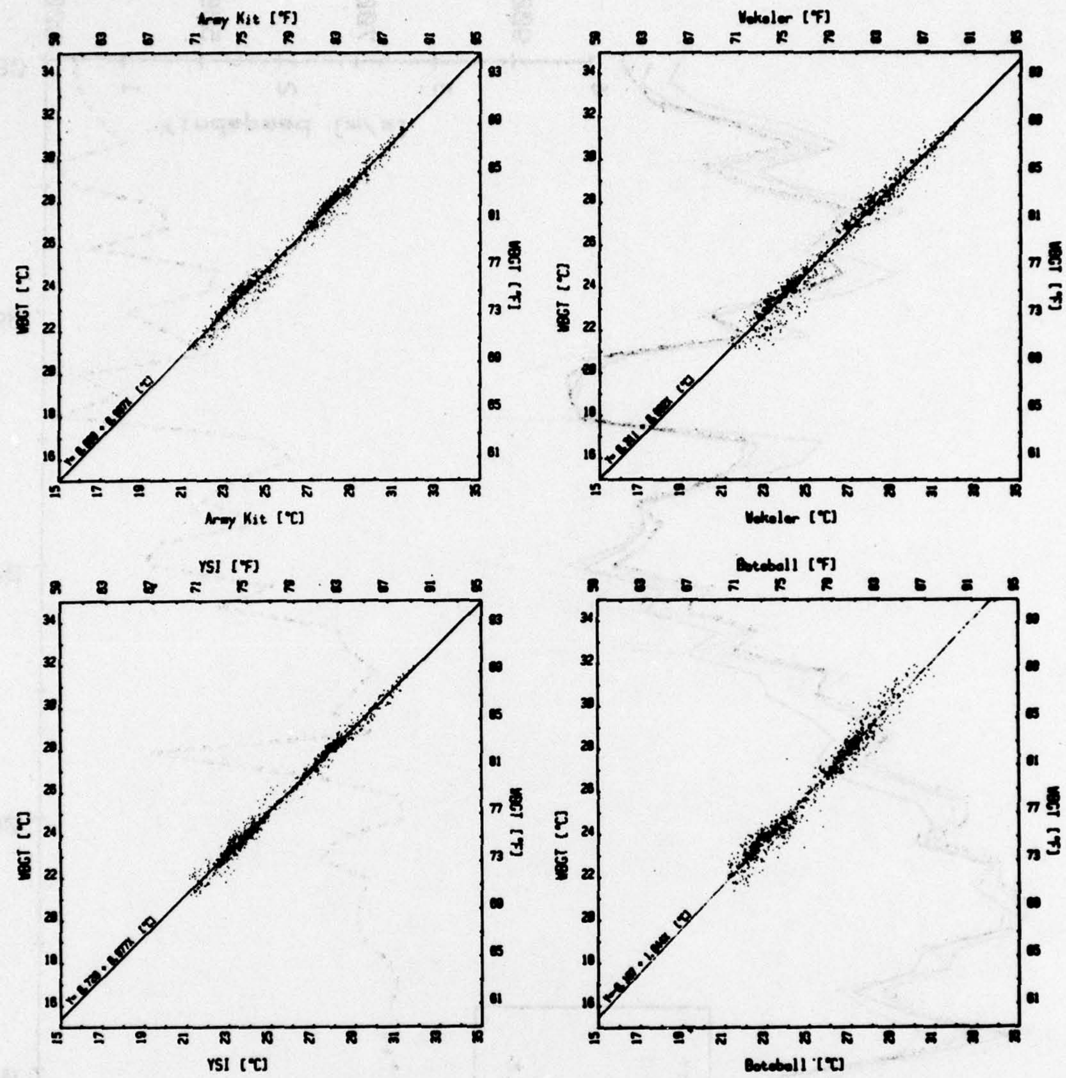

Fig. 15. Regression lines between instruments WBGT and Standard WBGT for all environments.

Table I. Regression equations between instruments WBGT and stnd. kit WBGT for all environments

INSTRUMENT	EQUATION	CORRELATION COEFFICIENT
Army kit	$y = 0.069 + 0.997x$	0.990
Weksler	$y = 0.311 + 0.982x$	0.981
YSI	$y = 0.728 + 0.977x$	0.994
Botsball	$y = -0.187 + 1.044x$	0.980

y = stnd. kit WBGT (^{o}C)
x = WBGT (^{o}C) from the instrument except for Botsball, where it is wet globe temperature

standard kit is not available commercially and can only be obtained on contract from any metal spinning company.

The thermometers in the Weksler kit are fragile and there is a tendency for the liquid columns to separate in the thermometers. In the case of Botsball the only fragile part is the glass on the dial of the thermometer.

Botsball costs less than the other instruments used in this study. If cost is not a factor, the YSI can be used as a suitable substitute for the standard kit.

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